Material Failure Mechanisms and Damage Models

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Key Words — Failure mechanism, Cause and effect

Reader Aids —
Purpose: Tutorial
Special math needed for explanations: None
Special math needed to use results: None
Results useful to: Designers and reliability engineers

Summary & Conclusions — Failures in engineering systems occur due to specific causes, whether foreseen or not; many of those causes are related to specific procedures by the user. Failures are typically attributed (correctly or not) to: ignorance and/or indifference about user needs and desires, inattentive management, poor selection of materials or combinations of materials, inadequate design, inappropriate manufacturing and assembly processes, lack of adequate technology, improper treatment by users, and other poor control of quality. Failure is a complicated concept; four simple conceptual models for failure are: *Stress*-strength, damage-endurance, challenge-response, and tolerance-requirement. The specific failure mechanisms depend on material or structural defects, damage induced during manufacture and assembly, and on conditions during storage and field use. Conditions that affect the state of an item are broadly termed *stresses (loads)*, eg, mechanical stress and strain, electrical current and voltage, temperature, humidity, chemical environment, and radiation. The effects of *stresses* are influenced by geometry, constitutive and damage properties of the materials, manufacturing parameters, and the application environment.

1. CONCEPTS

This paper introduces a tutorial series on material failure mechanisms and damage models; the purpose of this introduction is to familiarize non-specialists with the fundamentals of failure mechanisms in engineering assemblies. Subsequent tutorials will focus on particular failure mechanisms and will provide more details on the damage models.

The word, *stress* (*load*), is defined in the Summary & Conclusions; it is intended to be very general, as explained there. The word, *environment*, includes all *stresses* of all kinds, and is likewise intended to be very general.

1.1 *Conceptual Models for Failure*

It is tempting to think of a failure in a binary manner as something's being obviously broken or not. But most real failures are more complicated than that. Failures are due to a complex set of interactions between: a) the *stresses* that act on and within the system, and b) the materials/elements of the system. Each of the variables involved in the interactions usually must be treated as stochastic. Hence, a proper understanding of system reliability requires a deep understanding of the response of materials/elements to the *stresses* as well as the variability of each parameter. Four simple conceptual models for failure are defined here.

1. *Stress-strength*. The item fails if and only if the *stress* exceeds the strength. A non-failed item is good as new; if the *stress* does not exceed the strength, the *stress* has no permanent effect on the item, whatsoever. This failure model depends on the occurrence of critical events in the environment, rather than the mere passage of time or cycles. Strength is often treated as a random variable. Two examples of this model are: a) a steel bar in tension, and b) a transistor with a voltage applied across the emitter-collector.
2. *Damage-endurance*. A *stress* causes damage that accumulates irreversibly, as in corrosion, wear, fatigue, and dielectric breakdown. The cumulative damage does not degrade performance. The item fails when and only when the damage exceeds the endurance, ie, the damage accumulates until the endurance of the item is reached. Accumulated damage does not disappear when the *stresses* are removed, although sometimes annealing is possible. Endurance is often treated as a random variable.
3. *Challenge-response*. An element of the system is bad, but only when the element is challenged (needed) does it fail to respond, reveal itself as bad, and cause the system to fail. A common consumer example is the emergency brake on a car. Most computer program (software) failures are of this type. Telephone switching systems resemble this failure model, among others. This failure model depends on when critical events happen in the environment, rather than the mere passage of time or cycles. When failures of this type of failure model are rare in a system it is often extremely difficult to be sure that the challenge was correct, or exactly to what the failure was due.
4. *Tolerance-requirement*. A system performance characteristic is satisfactory if and only if its tolerance remains within the requirement, ie, failure occurs when something is nominally working, but not well enough. Example of this are a copier machine, and a measuring instrument. Any kind of gradual degradation of quality of performance of parts or systems can be represented by this model. □

This tutorial series introduces various failure mechanisms that can degrade the properties of materials. That degradation can cause the behavior (of a hardware item on which a user relies) to become inadequate due to one or more of the four conceptual models described in this section.

1.2 *Failure Mechanisms*

Failure mechanisms are the physical processes by which *stresses* cause damage to the elements comprising the system—

ultimately leading to failure by one or more of the conceptual models described in section 1.1. Understanding the potential failure mechanisms of a product is necessary to develop reliable products. The process of developing design guidelines is facilitated if quantitative models are available to describe the relevant failure mechanism(s). It is necessary therefore to identify the failure mechanisms that could be activated by the applied stresses during the life cycle of the system. For the purposes of this tutorial series, failure mechanisms are broadly grouped into overstress mechanisms and wearout mechanisms.

Table 1 lists generic failure mechanisms which can serve as potential agents of failure. Common failure mechanisms are included, except for failure processes encountered primarily in wafer-level integrated circuits, eg, dielectric breakdown, hot-electron, slow trapping, surface charge spreading, electromigration.

TABLE 1
List of Failure Mechanisms in Microelectronic Packages

List of Failure Mechanisms	
Overstress Failures	Wear-out Failures
Brittle Fracture	Wear
Ductile Fracture	Corrosion
Yield	Dendritic Growth
Buckling	Interdiffusion
Large Elastic deformation	Fatigue Crack Propagation
Interfacial De-adhesion	Diffusion
	Radiation
	Fatigue Crack Initiation
	Creep

It is wise to avoid the phrase, "random failure", because the phrase is so often misunderstood and/or misused to mean "without a cause". It is usually necessary to quantify our ignorance of the *stresses*, materials/elements, and other variables involved in failure mechanisms, by using stochastic (random) distributions and processes to represent them and/or their behavior. But even these stochastic characteristics cannot be quantified without an intimate knowledge of the variables, eg, a) geometry and material properties of the system, and b) *stresses* applied during manufacture, storage, handling, shipping, testing, use, and repair.

1.3 *Types of Stresses*

Another way to categorize failure mechanisms is broadly based on the nature of the *stresses* which trigger the mechanism: Mechanical, thermal, electrical, radiation, and chemical. These categories are neither complete nor mutually exclusive; they are merely a convenience for discussion.

- Mechanical failures result from elastic and plastic deformation, buckling, brittle and ductile fracture, fatigue crack initiation and propagation, creep and creep rupture. Many of the other types of failure mechanisms eventually do result in a mechanical failure, and mechanical failures (eg, a broken wire) can result in electrical failures.
- Thermal failures are a result of heating a component beyond its critical temperatures such as glass-transition temperature, melting point, or flash point. Thermal expansion and contraction can cause mechanical stresses.
- Electrical failures include those due to electrostatic discharge, dielectric breakdown, junction breakdown, hot electron injection, surface and bulk trapping, surface breakdown.
- Radiation failures may be caused by radioactive contaminants and secondary cosmic rays.
- Chemical failures are due to chemical environments which result in corrosion, oxidation, or ionic surface dendritic growth.

Often there are interactions among various types of stresses. For example:

- mechanical failure because of thermal expansion mismatch under a thermal stress
- stress-assisted corrosion
- stress-corrosion cracking
- field-induced metal migration
- temperature-induced acceleration of chemical reactions.

Not all of these mechanisms are relevant for any given system.

For convenience, the *overstress* mechanisms are summarized in section 2. The *wearout* mechanisms are summarized in section 3.

2. OVERSTRESS FAILURE MECHANISMS

2.1 *Large Elastic Deformation*

Failure can result from excessive elastic deformation, especially of a slender structure due to overstress. Analysis of such failures requires the use of the nonlinear theory of finite-deformation elasticity. Failures of this nature can be an issue in high-precision structures such as space mirrors and antennas, or in large flexible structures such as space antennas and solar panels where large deformations can trigger unstable vibrational modes. Examples of excessive elastic deformations in electronic packages include excessive flexing of bond wires resulting in intermittent cross-talk and/or shorts, or excessive deformation of flex-circuits causing stresses on terminations and solder joints.

2.2 *Yield*

By definition, stressing a component past its yield strength causes irreversible plastic strains, viz, permanent deformations. Such permanent deformations might not constitute a failure, depending on the application. This phenomenon typically applies for metallic components. Some metals behave almost perfectly plastically, while some exhibit appreciable strain hardening. Mechanical components such as cams, shafts, and gears are commonly heat treated to raise their yield strength in order to prevent plastic deformation. Yielding in electronic packages can occur, due to thermo-mechanical stresses, in metallic elements such as solder, bondwires, copper plated vias, and metallization.

2.3 *Buckling*

Buckling is caused by sudden catastrophic loss of elastic stability of slender structures under applied compressive stresses. The critical buckling stress is a function of material properties (eg, stiffness) as well as structural parameters (eg, slenderness ratio). In mathematical terms, buckling can be described as deformation along an unstable path orthogonal to the original deformation mode, and can be solved by eigenvalue theory and/or bifurcation theory. Buckling is a common design problem in compression-loaded columns encountered in civil engineering structures or in shear panels found in aircraft monocoque fuselage and wing structures. In electronic packages, examples of buckling are found in the wrinkling of thin films due to thermal expansion mismatch with the substrate, or in the collapse of leads in through-hole components due to excessive insertion force on misaligned components.

2.4 *Brittle Fracture*

Local microscale flaws can cause sharp stress concentrations in brittle materials, viz, those that exhibit little yielding and inelasticity before fracture. Excessive stress levels in brittle materials can cause failure by sudden catastrophic propagation of the dominant micro-flaw. A failure criterion based on local stresses is infeasible because linear elastic analysis predicts infinite stresses at the tip of the flaw or crack, regardless of the level of the applied far-field average or nominal stress. The basic approach in fracture mechanics is therefore one of predicting the level of the far-field stress at which the crack will locally propagate. The gross changes that occur in the elastic energy of a structure as a sharp brittle crack grows, can be compared to the energy required to produce new fracture surfaces, in order to calculate the average far-field stress (if no crack were present) which will cause local crack growth in a part. Griffith's analysis and experiments [2] reveal that failure is related not only to the magnitude of the applied far-field stress but also to the flaw size. A new measure is hence required to measure the severity of the stress. The concept of the stress-intensity factor provides just such a measure, since its magnitude depends both on the applied stress and the flaw size. The fracture-toughness of a brittle material can thus be measured in terms of its critical stress intensity factor at failure.

Quasi-brittle fracture can lead to failure in hardened metals and in ceramics. Thermo-set polymers can undergo extensive microcracking and crazing due to brittle cracking. Common examples of brittle fracture in electronic packages are cracking of glass seals and die materials. Brittle fracture can also occur due to the formation of brittle intermetallics in otherwise ductile materials like solder.

2.5 *Ductile Fracture*

Linear elastic theory of brittle fracture does not apply when there is gross plasticity at the crack tip due to overstresses. The concept of stress-intensity factor loses physical meaning and can no longer be applied to characterize the fracture toughness of the material. Griffith's energy concepts, however, still apply and the crack-tip energy release rate can be measured and used to predict ductile fracture. In mechanical engineering, such energy-based approaches are common in relatively ductile materials for high temperature applications, such as materials used for combustion chambers in engines, where plastic and creep deformations at the crack tip can no longer be ignored. In electronic packages, such situations arise in ductile inelastic materials such as solder, ductile electroless-deposited copper plating, aluminum and gold bond wires.

2.6 *Interfacial De-Adhesion*

Interfacial de-adhesion occurs at the interface between two adhering materials. One of the factors enhancing interfacial adhesive strength between two dissimilar materials is interdiffusion. The interfacial strength depends on the chemical and mechanical properties of the interface. Work is required to create an adhesive failure at the interface. Adhesion is a property measuring the maximum amount of mechanical work (energy) that can be transferred across an interface before separation. The work of separating an interface between two materials includes the work of adhesion as well as the work required to deform elastically/inelastically, the two bulk phases. In experimental terms, interfacial bonding strength is often characterized in terms of the electron binding energy between pairs of materials, and is a unique property of that pair. In practical mechanical terms, at a continuum length scale, the mechanical strength of the interface is characterized and measured in terms of the interfacial fracture toughness. This is a unique interfacial property between any pair of materials and can be measured in the laboratory for common choices of material combinations.

The most common examples in mechanical engineering applications are delaminations in laminated composite materials and adhesion failures in bonded joints. Common examples in electronic packages are failures at interfaces of a die and the attach material or at the interface of a wire bond and the bond pad.

3. WEAROUT FAILURE MECHANISMS

In general, wear, corrosion, and fatigue are the major causes of wearout failures in machinery, structures, and equipment. Wear and corrosion have been known for millennia. Fatigue was recognized only in the past century.

3.1 *Fatigue Crack Initiation*

When cyclic stresses are applied to a material, failure of the material occurs at stresses much below the ultimate tensile strength of the material, due to accumulation of damage. Fatigue failure begins with the initiation of a small, microscopic crack. The crack develops typically at a point of discontinuity or defect in the material which can cause local stress and plastic strain concentration. This is termed, fatigue crack initiation. Fatigue occurring due to large amplitudes of strain within 10^3–10^4 cycles is generally called low cycle fatigue. High cycle fatigue refers to failures occurring due to relatively low strain or stress amplitudes and occurring at greater than 10^3–10^4 cycles. The fatigue properties of a material can be characterized either by the (average) stress-life (S-N) curve or by the (average) strain-life curve for the material; these can be supplemented by adding probabilistic considerations. These curves plot the stress or strain amplitude against the average number of stress-reversals to failure, or the for particular percentages of items failing.

Fatigue is one of the most persistent problems in engineering design, ranging from failure of rotating shafts and reciprocating components to failure in aircraft, ships, and large civil engineering structures like bridges and buildings. In electronic packages, fatigue problems are commonly encountered in solder joints, bond wires, copper plated vias, etc.

3.2 *Fatigue Crack Propagation*

Once a crack has been initiated, the crack can propagate in a stable fashion under cyclic stresses, until it becomes unstable under the applied stress amplitude. The crack propagation rate is a material property and can be related to the cyclic range of stress intensity factor or energy release rates. It is not safe-design practice to design a component for fatigue crack propagation life. Instead, crack propagation characteristics can be used to specify inspection and maintenance schedules in engineering components and structures such as bridges, ships, airframes. This type of failure can be observed in electronic packages in die materials.

3.3 *Diffusion*

Diffusion refers to the time-dependent ability of an atomic, molecular, or ionic species to migrate within the bulk phase of a second material by atomic or molecular motion. From an atomic or molecular perspective, diffusion in solids is the migration of atoms or molecules from lattice site to lattice site. The atoms must have sufficient energy to break bonds and then reform them at another lattice site. This energy is the activation energy. In liquids, due to high mobility of molecules and ions, diffusion is faster and is governed by the concentration gradient. Thus diffusion is a wear-out mechanism whose rate is a characteristic material property and can be measured in the laboratory. Failure mechanisms such as corrosion, creep, dendritic growth, electromigration, interdiffusion, and outgassing are typically driven by diffusion phenomena. Diffusion is not usually a primary failure mechanism in mechanical, civil, or aeronautical engineering applications except indirectly because of its role in creep and corrosion. Diffusion phenomena are important in electronic packages, for example, in order to estimate moisture ingress rates into the package through seals, and through the case itself in the case of plastic packages. Moisture diffusion can be detrimental both from hermetic considerations as well as from hygro-mechanical stress and moisture-induced swelling. Diffusion phenomena can also degrade and age materials ranging from polycrystalline aluminum in interconnects by electromigration, to large-chain polymeric materials such as polyimides or epoxies frequently used in seals, attach, and printed wiring board materials.

3.4 *Interdiffusion*

When two different bulk materials are in intimate contact at a surface, molecules of one material can migrate into the other by diffusion and vice-versa. This phenomenon is called interdiffusion and provides interfacial adhesion. However if the effective diffusion rates for both materials are not equal, one of the materials may suffer a depletion of atoms, leading to Kirkendall voiding. Since diffusion is time-dependent, Kirkendall voiding also depends on time. This type of failure can be a hazard whenever two different materials are diffusion-bonded together. A common example in electronic packages is the leaching of gold into aluminum in wire bonds leading to *purple plague*.

3.5 *Creep*

Some materials such as thermoplastic polymers, solders, and many metals under mechanical stress at elevated temperature, can undergo time- dependent deformation due to dislocation climb mechanisms and polymer chain reorientation (self-diffusion) or due to grain boundary sliding and by intergranular or transgranular void migration (grain-boundary diffusion). The activation energy required for each of these creep mechanisms is a material property and depends on the temperature. Thus different creep mechanisms can dominate at different temperatures within the same material, and sometimes more than one creep mechanism can occur simultaneously. Designing for creep is a common issue in high temperature applications of metals, for example in material for power plant combustion chambers, exhausts, nuclear reactor pressure vessels, turbines. Thermoplastic polymers can display creep problems at relatively lower temperatures. Creep is commonly encountered in solder joints and in printed wiring board base materials at soldering temperatures in electronic packages.

3.6 *Corrosion*

Corrosion is the process of chemical or electrochemical degradation of materials. Common forms of corrosion are uniform, galvanic and pitting corrosion. The corrosion reaction rate depends on the parent material, an electrolyte with ionic contaminants, geometric factors, and local electrical bias.

Uniform corrosion is a chemical, or electrochemical, reaction occurring at the metal-electrolyte interface uniformly all over the surface. The continuation of the corrosion process and its rate depend on the nature of the corrosion product. If the corrosion product is soluble in water, then it can be washed off, thus exposing fresh metal for further corrosion. If the corrosion product forms an insoluble, non-porous, adherent layer, it limits the rate of reaction and can finally stall the process.

Galvanic corrosion occurs when two or more different metals are in contact. Each metal has a unique electrochemical potential. Hence, when two metals are in contact, the metal with the higher electrochemical potential becomes the cathode (where a reduction reaction occurs) and the other metal becomes the anode (where an oxidation reaction, or corrosion, occurs). Thus a galvanic cell forms. The rate of galvanic corrosion is governed by the rate of ionization at the anode (ie, the rate at which anode material passes into solution, and this in turn depends on the difference in electrochemical potential between the two metals in contact). The larger this potential difference, the higher is the rate of galvanic corrosion. Because charge is conserved, the rate of galvanic corrosion also depends on the rate of cathodic reactions. The ratio of cathode-area to anode-area greatly affects the rate of galvanic corrosion.

Pitting corrosion occurs at localized areas causing the formation of pits. The corrosion conditions produced inside the pit accelerate the corrosion process. As the positive ions at the anode go into solution, they get hydrolysed and produce hydrogen ions in the process. This increase in acidity in the pit destroys the adhering corrosion products, exposing more fresh metal to attack. Since the oxygen availability in the pit is low, the cathodic reduction reaction can occur only at the mouth of the pit, thus limiting lateral growth of the pit.

Surface oxidation is another common type of corrosion in metallic materials and is governed by the free energy of formation of the oxide. For example, there is a large driving force for the oxidation of aluminum and magnesium, but much less of a force for copper, chromium, and nickel. The properties of the oxide layer often dictates the rate of continued corrosion, since densely packed oxide layers at the surface can act as a protective layer for the bulk material within, unlike a porous, low-density oxide layer. Experts differ about the precise nature of the protection offered by these oxide films.

Corrosion is a very pervasive problem in all engineering structures, especially those in harsh chemical environments such as chemical engineering processing equipment, in salty environments such as naval structures, off-shore oil rigs, bridges. Corrosion is a common problem in all metallic sites in electronic packages and needs careful consideration. Many of these corrosion problems are well documented, and their prevention measures are known. However, corrosion failures continue to occur. Most corrosion problems result from a violation of fundamental principles.

3.7 *Stress Corrosion Cracking*

Stress corrosion cracking is an interaction between the two mechanisms of fracture and corrosion that occurs because of the simultaneous action of mechanical stress and corrosion phenomena. It occurs because of stress concentration at corrosion-generated surface flaws (as quantified by the stress intensity factor); when a critical value of stress concentration is reached, mechanical fracture occurs. Although stress concentration does occur at such flaws, the stresses do not exceed the critical value required to cause mechanical fracture of the material in an inert environment. Thus, stress corrosion essentially reduces the fracture strength of the material. The process is synergistic, ie, it is the combined simultaneous interaction of mechanical and chemical forces resulting in crack propagation whereas neither factor acting independently would produce the same result.

3.8 *Dendritic Growth*

This is essentially an electrolytic process. It is observed in electrically biased tests where the metal from the anode region migrates to the cathodic areas and forms dendrites there. The metal migration leads to an increase in leakage current between the bridged regions or causes a short if complete bridging occurs (migrating resistance shorts). Although silver migration has been most widely reported, depending on environmental conditions many other metals like lead, tin, nickel, gold, and copper do migrate.

Metal migration is governed by: availability of metal, presence of condensed water and ionic species, and the existence of a voltage differential. First, the metals known to show metal migration (Pb, Sn, Ni, Au, Cu, Ag) should be exposed to the atmosphere. As the migration phenomenon is an electrolytic process, it is essential to have a conducting medium, eg, water with dissolved ionic species. The ionic species can be impurities like chlorides or products generated during corrosion. Finally, the driving force necessary to cause metal migration is an electrical potential difference.

3.9 *Wear*

Wear is the erosion of material whenever two surfaces in contact experience relative sliding motion under the action of a contact force. Wear can be adhesive, abrasive, or in the case of liquid-cooled devices by liquid erosion of cooling ducts caused by cavitation. Wear rate is usually a material property and directly related to the hardness of the material. Surface treatment to increase hardness can therefore increase wear resistance. Wear erosion can result in uniform removal of material as in the case of wear-away of piston-rings in reciprocating internal combustion engines or as in descaling due to sandblasting or shot blasting. On the other hand, wear erosion can also be nonuniform as in the case of pitting in gear teeth, cam surfaces, etc. Cavitation wear in conduits carrying liquids also produces nonuniform pitting. Adhesive wear is common in connector mating surfaces in electronic packages.

3.10 *Radiation Damage*

Particle radiation is common in aerospace environments such as satellites, spacecraft, and high-altitude aircraft and in terrestrial environments such as nuclear-power, and particle-research establishments. Radiation damage can take two different forms: 1) mechanical failure mechanism, and 2) more serious electrical damage mechanism. The mechanical failure mechanism is embrittlement; the electrical phenomenon is more of an unpredictable overstress and causes *soft errors* due to passage of single radiation particles through VLSI (very large-scale integration) circuitry.

Radiation damage causes various types of aging in different types of materials. Radiation damage is of concern in metallic, ceramic, and polymeric materials. In metals and ceramics, radiation causes point defects such as pairwise combinations of vacancies and interstitial atoms (Schottky defects) by knocking atoms out of molecular lattice structures. These point defects cause embrittlement aging which can be countered by annealing. More importantly, in electronic packaging applications, these defects also alter the thermal, optical, and electrical properties—impairing the operation of active devices. In polymeric materials, radiation aging is caused by breaks in polymer chains, or by changing the degree of polymerization due to chain branching. Either of these can reduce the strength of the polymer. In its most common form, this can lead to photodegradation of polymers under prolonged exposure to the ultraviolet radiation in strong sunlight. Stabilizers are sometimes needed to combat such failures. Material aging problems due to radiation damage are commonly encountered in space-craft and satellite materials.

The electrical failure modes caused by radiation are important in electronic packages because they dictate, in part, the choice of packaging materials and the impurities therein. Further, radiation shielding might be an important consideration in the package design and configuration. Radiation effects on microelectronics can become a very serious obstacle to further rapid increase in VLSI density. The radiation effects are particularly important in memory chips, which usually lead other microelectronics technologies in advanced development. Cosmic rays or radioactive contaminants can produce single events in most modern microelectronics. A single event is an event that is caused by the passage through the microcircuit of a single high energy particle: electron, photon, muon, pion, or alpha. A single event upset (soft error) is a change of logic state. The upset is unpredictable, nonrecurring, and temporary, ie, no physical defects are associated with the error, and the failed bit is recovered by the next clock cycle.

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Manuscript TR91-130 received 1991 April 10; revised 1991 August 21.

IEEE Log Number 03802 ◄TR►

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